

growth is at least 500° C., preferably at least 650° C. The surface can be exposed to the treatment condition in stages of different temperatures, different oxidizing powers, or both. For example, the surface could be treated at 650° C. for a time and then heated to 1000° C. and kept at 1000° C. for an additional time. Such controlled and staged surface treatment can generate a surface structure of a desired morphology and composition.

[0081] Superior oxide coatings result from preheating to about 1000° C. (in some embodiments at least 900° C.) under an inert, or preferably, a reducing atmosphere such as a H<sub>2</sub>-containing atmosphere (preferably at least 1000 ppm H<sub>2</sub>, in some embodiments 1 to 100% H<sub>2</sub>). Preheat under a reducing atmosphere was observed to produce superior oxide coatings with little or no spalling. It is believed that this control of preheat conditions results in superior coatings because it minimizes the formation of nickel oxide or mixtures of oxides. Great care must be taken selecting a truly "inert" atmosphere because atmospheres conventionally considered as inert atmospheres yield inferior results. That is because nickel oxide can theoretically form even at 10<sup>-10</sup> atm oxygen and chromia at 10<sup>-21</sup> atm oxygen; such extreme levels of purity are not available in commercially available gases. Therefore, reducing atmospheres are preferred.

[0082] Conventional wisdom is that the higher the temperature, the faster the oxidation rate. Surprisingly, we discovered that the oxide grew faster at 1000° C. than at 1050° C. One possible explanation is that the high temperature oxide could be denser, thus discouraging faster growth. The lower temperature oxide could be more porous thus allowing faster oxide growth. On the other hand, too high a temperature will promote interdiffusion between the aluminide layer and the substrate, and the aluminide will disappear into the bulk of the alloy. Therefore, the thermally-grown oxide is preferably conducted in the temperature range of 1000 to 1100° C., more preferably 1025-1075° C. In the presence of excess oxygen, for example flowing air, the oxidation treatment is preferably conducted for 30 to 6000 min, more preferably 60 to 1500 min.

[0083] It should be recognized that the term "alumina" can be used to refer to a material containing aluminum oxides in the presence of additional metals. In the descriptions herein, unless specified, the term "alumina" encompasses substantially pure material ("consists essentially of alumina") and/or aluminum oxides containing modifiers.

[0084] Thinner layers are less prone to cracking; therefore, the thermally-grown oxide layer is preferably 10  $\mu$ m thick or less, more preferably 5  $\mu$ m thick or less, more preferably preferably 1  $\mu$ m thick or less, and in some embodiments is 0.1  $\mu$ m to 10  $\mu$ m thick, in some embodiments is 0.2  $\mu$ m to 5  $\mu$ m thick, in some embodiments is 0.5  $\mu$ m to 3  $\mu$ m thick. Typically, these thicknesses are measured with an optical or electron microscope. Generally, the thermally-grown oxide layer can be visually identified; the underlying aluminide layer is metallic in nature and contains no more than 5 wt % oxygen atoms; surface washcoat layers may be distinguished from the thermally-grown oxide by differences in density, porosity or crystal phase.

[0085] The aluminized surface can be modified by the addition of alkaline earth elements (Be, Mg, Ca, Sr, Ba), rare earth elements (Y, La, Ce, Pr, Nd, Pm, Sm, Eu, Gd, Th, Dy,

Ho, Er, Tm, Yb, Lu) or combinations of these. The addition of these elements is followed by a reaction with an oxidizing atmosphere to form a mixed oxide scale. When the modifying element is La, for example, the scale contains LaAlO<sub>3</sub>, lanthanum aluminate. In some embodiments, a stabilized alumina surface can be formed by adding a rare earth element such as La.

#### [0086] Flow Rates

[0087] The aluminide layer is preferably formed by reacting a surface with a gaseous reactant mixture under dynamic flow conditions. The aluminum needed for aluminide formation can be deposited in a microchannel by flowing AlCl<sub>3</sub> and H<sub>2</sub> into a microchannel. In a multichannel device, the Al can be deposited only on selected channels (such as by plugging certain channels to exclude the aluminum precursors during a CVD treatment). The aluminum layer can also be applied onto selected portions of a microchannel device by controlling relative pressures. For example, in a microchannel device that contains at least two channels separated by a wall and in which the two channels are connected to each other via orifices in the wall, AlCl<sub>3</sub> flows through a first channel while H<sub>2</sub>, at a higher pressure, flows through a second channel and through the orifices into the first channel.

[0088] Static gas treatments can be conducted by filling the desired areas with the reactive gases with interim gas pumping if needed.

[0089] Based on a detailed analysis of the tested devices, the following thresholds were established:

[0090] Wall Shear Stress: To ensure drag forces do not impair the formation of aluminization coating, the wall shear stress should not exceed 50 Pa if the aluminization gases are flowing through a jet orifice. Allowable wall shear stress should not exceed 200 Pa if the aluminization gases are not impinging on the wall of a microchannel as through a jet orifice.

[0091] Wall Dynamic Pressure: To ensure momentum impact erosion does not impair the adequate formation of aluminization coating, the wall dynamic pressure should not exceed 10 Pa if the aluminization gases are flowing through a jet orifice. Substantially higher wall dynamic pressure is allowed in the absence of a jet orifice. Allowable wall dynamic pressure should not exceed 100 Pa if the aluminization gases are not impinging on the wall of a microchannel as through a jet orifice.

#### [0092] Practical Application

[0093] The metrics presented above are used to determine the flow configuration and individual inlet flow rates that will imply good aluminization treatment from a fluidics standpoint. Generally there is a combination of possible input and output flow paths for a device. CFD predictions are used to determine those inflow/outflow combinations and the individual inlet flow rates that will result in globally maintaining the wall shear stress below 50 Pa, and the wall dynamic pressure below 10 Pa throughout the entire device if flow of at least one of the aluminization gases is through a jet orifice. The maximum allowable inlet flow rate that satisfies these two criteria and the associated flow configuration becomes the recommended procedure for aluminizing